Small Changes with Big Consequences: Solar System Stability

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Motivation

- How much change is too much?
- How likely is a stellar flyby?
- What are the mechanisms for instability?

Methods

- 2,880, 4.8 Gyrs solar system simulations
- NASA JPL Horizons, J2000 epoch
- `REBOUND` N-body integrator
- `REBOUNDx` with gr_potential
- `WHCKL` integrator
- dt = 8.062 days

Secular Resonances

- The most likely path to instability is by a secular resonance between Mercury and Jupiter.
- A g_1–g_5 resonance drives an increase in the eccentricity of Mercury and can lead to a collision with Venus.
- The secular dynamics of the solar system are coupled together so that, over time, the changes to Neptune's orbit are felt by Mercury, see Figure 1.
- A secular resonance between Earth and Mars is shown in Figure 2.

Changes to the secular modes of the solar system are proportional to the change in Neptune's orbit.

Figure 1

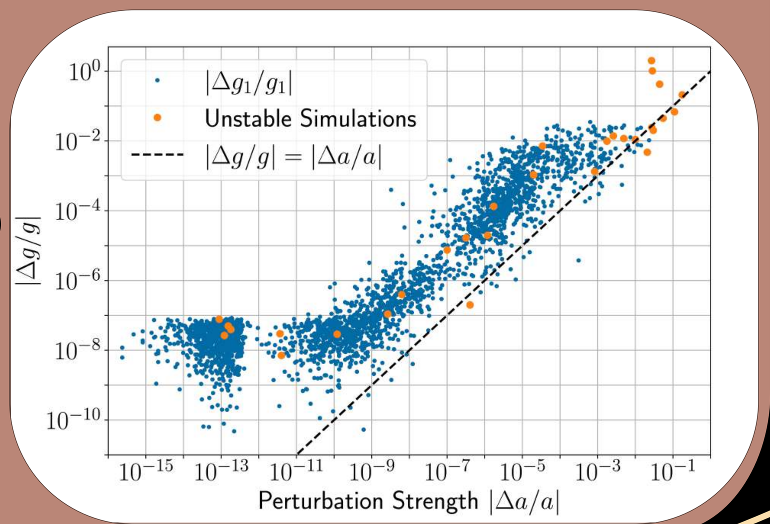
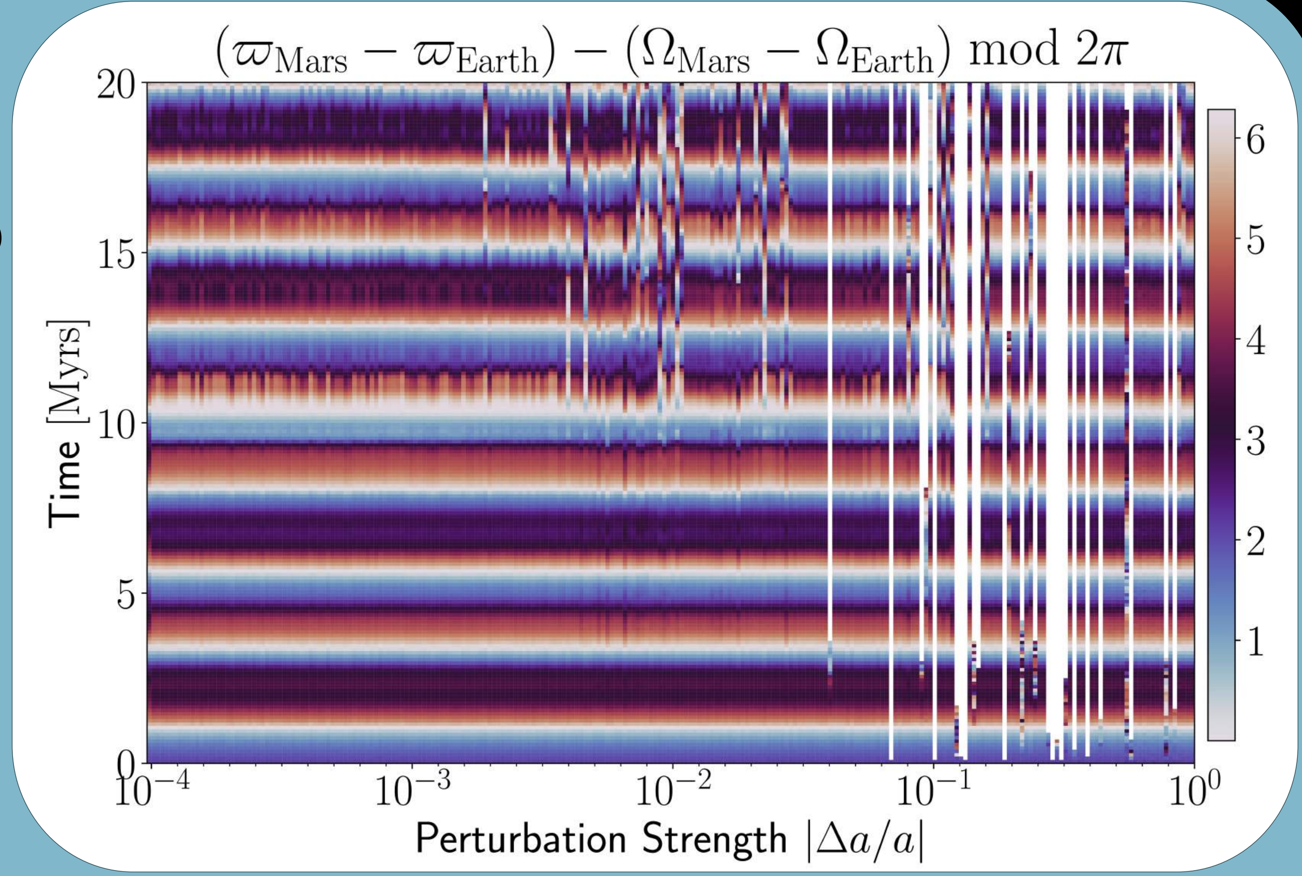


Figure 2



Earth–Mars secular resonance for 240 simulations.
- Changes to Neptune's orbit as small as 0.1% can alter the resonant structure of the inner solar system.
- Nearly instantaneous instability begins around 10%.

Expected Flyby Rates

- We can compute the flyby rate for each stellar environment using the stellar density, mass, and velocity distributions.
- At very large distances or small masses the influence of passing stars are essentially imperceptible.
- With a well-defined cross-section, we can define an encounter rate as the rate in which stars enter a sphere of influence around the Sun.
- Although a flyby is very unlikely to directly alter the orbit of Mercury, secular interactions will eventually propagate perturbations of the outer planets' orbits to Mercury's orbit.
- Weaker, successive flybys **do not** cumulatively build up over time to cause catastrophic effects. Only critical flybys matter.

Average time until a stellar flyby for various stellar environments.
- Flybys that change the outermost orbit by more than 0.1% are strong enough to affect the system's long-term stability.
- Perturbation strength is the relative change in the semi-major axis of Neptune due to a flyby.

Figure 3

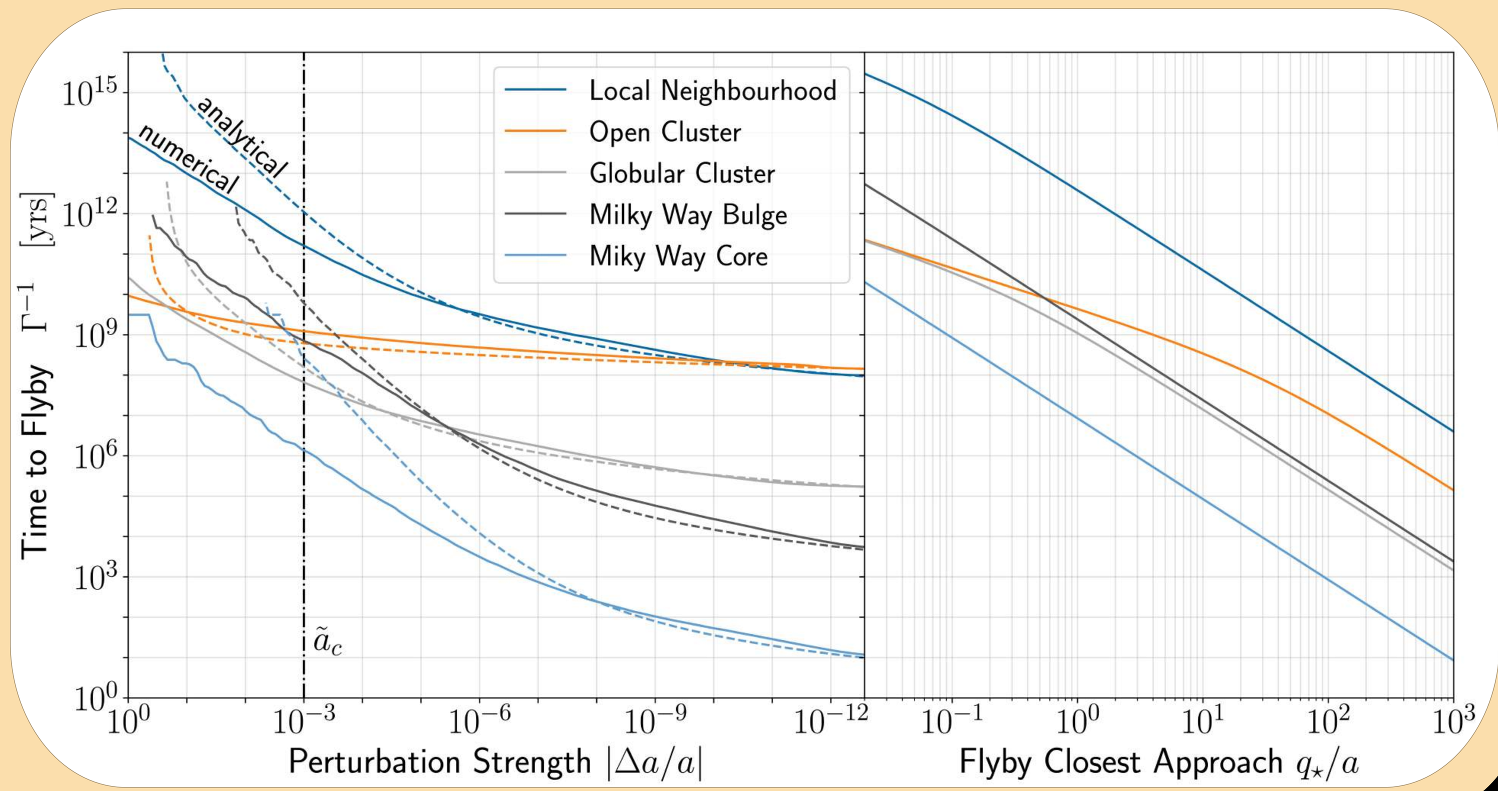
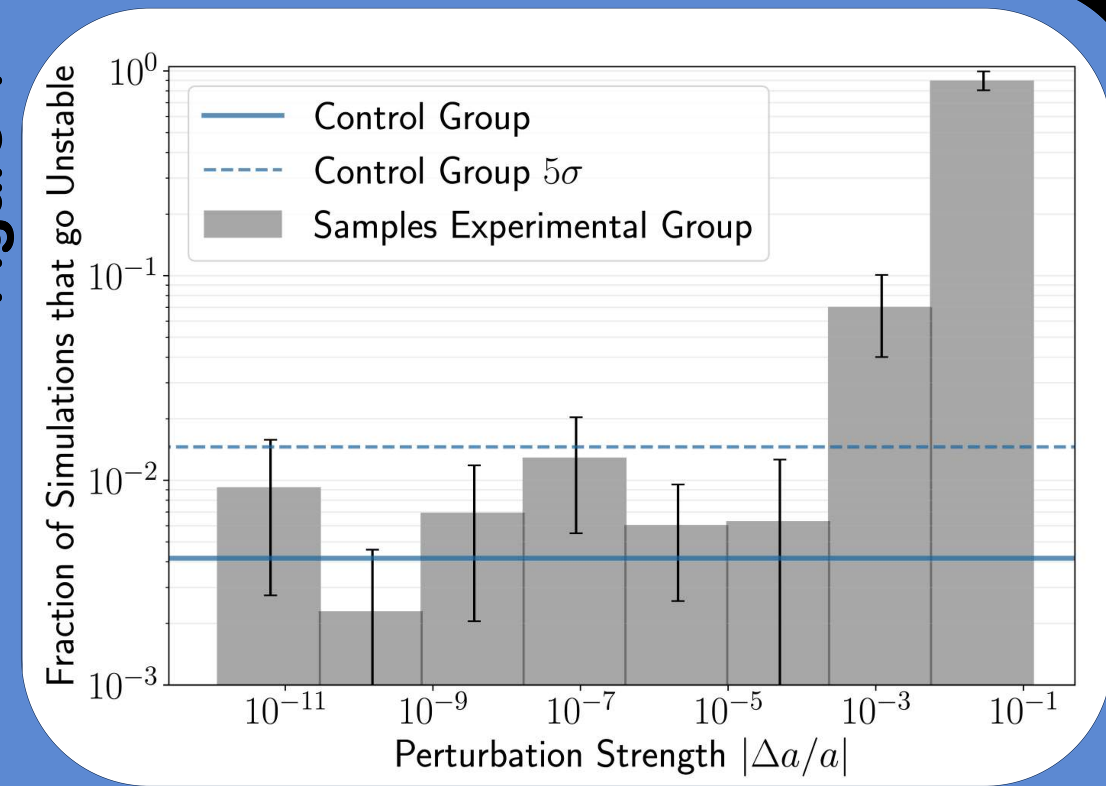


Figure 4



The fraction of simulations that lead to an instability before 4.8 Gyrs.
- For relative changes to Neptune's orbit larger than 0.1%, the instability fraction is 5σ more than in the control group, going from 0.4% to 7%.

Conclusions

- A change of 0.1% to the semi-major axis of Neptune can increase the chance of solar system instability by 10x.
- We don't expect a flyby would critically alter the solar system within the next 100 Gyrs.
- Due to chaos, there is no one-to-one map between changes to the secular frequencies and dynamical instability, but we see a strong correlation.

The distance to the Sun for these blue and white lines differ by 0.1%

References

Adams 2010
Batygin+ 2015
Cai+ 2017, 2019
Chabrier 2003
Bailer-Jones+ 2018
Heggie 2006
Jiménez-Torres+ 2013
Laskar+ 2011
Laskar 1988, 1989, 1990, 1993, 2000, 2003, 2012
Laskar & Gastineau 2009
Li & Adams 2015
Lithwick & Wu 2011
Malmberg+ 2011
Mogavero & Laskar 2021, 2022
Murray & Dermott 1999
Portegies Zwart & Jílková 2015
Rein, Brown, & Tamayo 2019
Rein & Liu 2012 <— REBOUND
Rein, Tamayo, & Brown 2019
Roy & Haddow 2003; Salpeter 1955
Spurzem+ 2009; Stock+ 2020, 2022
Tamayo+ 2020; Wisdom & Holman 1992
Zakamska & Tremaine 2004; Zeebe 2015
Zheng, Kouwenhoven, & Wang 2015
Zink, Batygin, & Adams 2020